Estimation of the annual yield of organic carbon released from carbonates and shales by chemical weathering

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Abstract

The aim of this paper is to propose an initial estimation of the annual organic matter yield induced by chemical weathering of carbonates and shales, considering their global surface at outcrop and their organic matter content. The calculation also uses data on river fluxes resulting from carbonate rocks and shales weathering in major world watersheds, published by numerous authors. The results obtained from the studied watersheds have then been extrapolated to a global scale.

Despite rather large uncertainty to such an approach, the calculated value of ca. 0.1 Gt implies that the annual organic carbon yield related to carbonates and shales chemical weathering might be a non-negligible component of the global carbon cycle. The individual contributions of different watersheds necessarily depend on the organic matter content of altered rocks. They are also obviously controlled by climatic parameters.

The calculated yields do not constitute a direct supply to soils and rivers because of mineralisation when organic carbon is brought in contact with the atmosphere. Even so, the release of fossil organic matter would have implications for the global carbon cycle through the efficiency of the global chemical weathering as a carbon sink. Whatever the chosen hypothesis, the results of this study suggest that the recycled organic yield is a neglected component in the global organic carbon cycle assessment. Because it exists and, in addition, because it might represent a non-negligible carbon pool, fossil organic carbon deserves to be taken into account for a better evaluation of the organic stocks in soils and rivers presently only based on climatic data and current vegetal production.

Author Keywords: global organic carbon cycle; organic matter; carbonated rocks; chemical weathering; soils; rivers

1. Introduction

The knowledge of the global terrestrial organic carbon pool (soils, rivers) is one of the key components of the global organic carbon cycle understanding (Arthur; IPCC and IPCC). Several authors have estimated the amount of organic carbon stored in soils both globally and regionally (Eswaran; Balesdent; Batjes; Adams and Carter). Furthermore, the organic carbon load in rivers is also well documented (Holland; Berner; Degens; Probst; Amiotte; Ludwig and Aitkenhead). All these various studies rely on the prerequisite that the organic carbon occurring in soils or loaded in the rivers mainly originate from the current or the post-glacial vegetal cover production.

These studies do not take into account the contribution of fossil organic matter (inherited/recycled organic matter) derived from weathering of sedimentary rocks. Such contribution is well known (Tyson, 1992) and has been well studied (Dow and Disnar). Artru (1972) and Alpern (1980) reported upon reworked black organic particles, respectively in Callovo-oxfordian marls of the southeast of France and Toarcian marls of the Paris basin (France). Guy-Ohlson et al. (1987) observed reworked Carboniferous spores in Swedish Jurassic Rocks. Such reworked organic particles can also be used in the determination of sedimentary cycles (Gregory and Eshet). The occurrence of reworked organic particles has also been observed in modern marine sediments. As an example, the amount of reworked palynomorphs of the observed particles in such sediments varies from 80% in the Norway Sea (Combaz and Combaz) to 50% in Hudson bay (Bilodeau et al., 1990) and Antartic shelf (Groot and Truswell) and 30%±25 in open ocean (Groot and Groot, 1971). It does not exceed 10% in the Black Sea (Traverse, 1974), the northeast of the Pacific shelf of North America (Heuser and Balsam, 1977), the eastern USA slope (Heuser and Balsam, 1985) or the eastern Canadian shelf (Mudie, 1982). Reworked organic particles have also been observed in modern palustrine sediments (marais maudit; Boulen, 2000), fjords sediments (Syvitski et al., 1990) and lacustrine sediments (Lake Michigan— Hough and Wilson; Lake Ontario— Kemp and Johnston, 1979; Lake Chaillexon— Di and Di; Lake Annecy— Buillit and Noel). It has been pointed out in lake-derived water supplies (Johnson and Thomas, 1884) and in rivers sediments (Chaillexon basin— Di-Giovanni et al., 2000a; Draix basin— Di-Giovanni et al., 2000b; Rhône delta—Gadel and Ragot, 1973). Finally, recent studies have also shown the occurrence of fossil organic matter in various French soils (Lichtfouse; Di; Di and Di).

Considering that sedimentary formations represent 66% of the rock of the Earth's surface (Blatt and Jones, 1975), it can been easily assumed that the question of the fate of their original organic matter content during weathering deserves to be taken into account for a better understanding of the present and past global organic carbon cycle. Note that such questions has been recently mentioned by Ludwig (2001) regarding an isotopic study of riverine export of aged terrestrial organic matter to the North Atlantic Ocean (Raymond and Bauer, 2001).

The aims of this paper are, firstly, to examine the various factors intervening in the release of fossil organic matter from major sedimentary formations and, secondly, to propose an initial estimation of the annual organic yield originating from the chemical weathering of carbonates and shales in the major world watersheds and at the global scale.

2. Studied areas and method

Carbonate dissolution is a process, the rate of which is ruled by physical and biological environmental conditions (relief, vegetation), hydro-climatic factors (precipitation, drainage, evaporation and temperature) and anthropogenic actions (pollution, deforestation, cultivation) (Aubert; Callot; Pochon; Gaiffe and Campy). The consequential calcium release and output under the dissolved state in running and percolating waters leaves insoluble residues that accumulate on the Earth's surface. These residues are the main components of surficial formations such as flint clay (Gosselet; Matthieu and Laignel), “les terres d'aubues” (Baize, 1972), “terra fusca”, and “terra rossa” (Lamouroux, 1972). The accumulations of these residual materials provide evidence for a global annual, non-negligible, detrital organic and mineral yield from geological formations. For example, Gaiffe (1987) showed that the insoluble residue resulting from the Kimmeridgian limestone weathering, with organic amounts not exceeding 0.2%, in the Jura mountains (France) can contain up to 15% of organic matter. As a first approach, such an observation supports the possibility of simply determining the annual organic yield resulting from carbonate rocks weathering from the starting organic carbon rock content and the final amount of residual OM. We can assume the following calculation principle. The dissolution of rocks that contain carbonates produces dissolved carbonates and an insoluble residue that can contain organic matter if the parent rocks contained organic matter. If the dissolved carbonates yield produced and the initial carbonate content of the parent rock are known, we can calculate the insoluble residue yield released. In addition, if the initial organic content of the parent rock is also known, we can then quantify the theoretical organic yield released.

In detail, to apprehend the global scale, this study is focussed on the worlds major watersheds (Fig. 1). The physical characteristics of the watersheds (slopes, surfaces) were determined by Pinet and Souriau (1988). The amounts of river-borne matter resulting from mechanical and chemical weathering were estimated by Probst (1992) and Amiotte-Suchet (1995). For each of these watersheds, the estimation of the dissolved carbonates amounts (F_{CaCo3}) in t/year has been achieved considering the specific bicarbonate average annual flow (in mol/year) resulting from the dissolution of the carbonated rock weathering, calculated by Amiotte-Suchet (1995). Knowing the average carbonate content in the sedimentary rocks considered, i.e. carbonates or shales, in each watershed (Ronov and Garrels), it was possible to determine the theoretical annual yield of insoluble residues in t/year.

$$\mathrm{Rs}=(F_{\mathrm{CaCO3}}/\mathrm{Cas})\cdot \mathrm{rs}$$
$$\mathrm{Rc}=(F_{\mathrm{CaCO3}}/\mathrm{Cac})\cdot \mathrm{rc}$$

with: Rs=insoluble residue produced by shales weathering (t/year); Rc=insoluble residue produced by carbonates rocks weathering (t/year); Cas=$CaCO_3$ content of the SHALES=6%; RS=insoluble residue content of the SHALES=94%; Cac=$CaCO_3$ content of the CARBONATES=75.8%; RC=insoluble residue content of the CARBONATES=24.2%.

The organic carbon content of the calculated residues (CoRc and CoRs) has been estimated by using the average organic content of sedimentary rocks, according to Ronov and Yaroshevsky (1976):

CoRc (%)=Coc/rc
CoRs (%)=Cos/rs

with: Cos=average content of organic carbon of the SHALES=0.8%; Coc=average content of organic carbon of the carbonate ROCKS=0.06%.

All these data allow an initial estimation of the annual inherited organic matter yield to be made, for each major watershed (OY, t/year).

$$\mathrm{OY}=[(\mathrm{Rs}\cdot\mathrm{CoRs})(\mathrm{Ss}/(\mathrm{Ss}+\mathrm{Sc}))]+[(\mathrm{Rs}\cdot\mathrm{CoRc})(\mathrm{Sc}/(\mathrm{Ss}+\mathrm{Sc}))]$$

with: Ss=shale surface area (km^2); Sc=carbonates surface area (km^2).

An estimation of the bedrock organic yield on a global scale has been achieved by extrapolating the results obtained of the major watersheds to the total of the continental surfaces. The studied watersheds have been classified according to the five morpho-climatic types defined by Meybeck (1979): arctic zone, temperate zone, arid zone, humid tropical zone, and contrasted tropical zone, where surface conditions vary between arid and humid tropical ones. Note that the 36 basins studied represent 52% of the arctic zone, 40% of the temperated zone, 18% of the arid zone, 64% of the contrasted tropical zone and 53% of the humid tropical zone.

The organic yields for each climatic zone is obtained by the following formula:

OYzc=OYbv(Szc/Sbv)

with: OYzc=annual organic yield of the climatic zone considered (t/year); OYbv=annual organic yield of the major watersheds studied in the climatic zone considered (t/year); Szc=surface area of the climatic zone considered (according to Amiotte-Suchet, 1995) (km^2); Sbv=surface areas of the total major watershed studied in the climatic zone considered (km^2).

The global annual yield of the carbonated rocks represents the sum of the annual organic yield of the five considered climatic zones.

3. Results

There are wide variations of the annual inherited organic carbon yield among the major world watersheds (Table 1). The calculated values range from zero in the basins without carbonate rocks (e.g. Limpopo, Negro) to more than 9 million t in the Amazon basin. There are also very wide variations between specific yields calculated for each of the studied watersheds, the maximum values being those obtained for the Pô and the Rhone with figures of 9900 and 6700 $kg/km^2/year$, respectively (Table 1).

By extrapolating the results obtained on watersheds, we made a first assessment of the organic yield of shales and carbonates for each of the climatic zones and for the whole world (Table 2). The global annual yield is estimated at 0.1 Gt/year (or Pg/year) representing an average of 977 $kg/km^2/year$. As expected, there are wide variations of the yield between the various climatic zones (Fig. 2). The humid tropical zone represents 38% of the global yield, the arctic zone 25%, the temperature zone over 20%; the arid tropical contrasted zones 14 and 2%, respectively. Obviously, these large variations depend (Table 2; Fig. 3) on the surface of the climatic zones considered (the highest production value corresponds to the humid tropical zone that covers the largest surface; the smallest yield corresponds to the contrasted tropical zone which covers the smallest surface). They also depend on other factors such as the climate and/or the mean bedrock organic carbon content in the study area. The importance of such factors might be better appreciated when considering the yield values by surface unit. These latter ones decrease in the following climatic zone order: temperate: 1417 $kg/km^2/year$; humid tropical: 1302 $kg/km^2/year$; arctic 1042 $kg/km^2/year$; contrasted tropical: 123 $kg/km^2/year$; and arid: 698 $kg/km^2/year$. For example, the difference of organic carbon yield per surface unit between the arid and the humid tropical zones cannot be explained by the bedrock organic content since it is the same in both cases: 0.2% (Fig. 3). This is most likely due to the very large difference of precipitations between these two areas. In contrast, the very low organic yield value in the contrasted tropical zone (123 $kg/km^2/year$) is due to the very low organic carbon content of the corresponding geological substratum. This positive relationship between the recycled organic carbon yield and the bedrock organic carbon content is also remarkable when examining the results of the major watersheds in each climatic zone (Fig. 4), and more specifically in the temperate and arctic zones. However, Fig. 4 (arid, contrasted and humid zones) shows that the organic yield is not only explained by the bedrock organic carbon content and that other factors such as topography or local precipitation patterns might be taken into account.

4. Discussions

4.1. A non-negligible component of the carbon cycle

The proposed values for the organic yield of carbonates and shales represent an initial estimation of the amount of organic matter potentially originating from the chemical weathering of carbonated rocks. They largely depend on the approximations due to the global scale evaluation of the parameters concerning bedrocks (surfaces, organic matter content). They consider the organic yield resulting from the chemical weathering of carbonated rocks (carbonates or shales) although it is well known that such weathering can also affect non-carbonated rocks (Loughnan; Dejou; Ildefonse; Tardy; Probst; Gay and Amiotte) and, more specifically, clays that might contain large amounts of organic matter (Huc and Huc).

These initial values suggest that there is a significant annual organic yield from sedimentary rocks (0.1 Gt/year) that is actually a non-negligible component of the carbon cycle. It is a small amount when compared to 45–50 Gt of organic carbon produced annually by the world's vegetal cover (Ajtay and Houghton). However, it is of the same order of magnitude than the amount of organic matter that is annually transported by rivers, i.e. 0.066–0.174 Gt/year (Kempe; Meybeck; Ludwig and Aitkenhead).

4.2. The problem of its mineralisation

This annual inherited organic yield does not necessarily mean a direct supply to soils and rivers. It must take into account that at least part of the produced organic matter produced by weathering of carbonated rocks can be mineralised and produces CO_2 ($C_6H_{12}O_6$—glucose+6 $O_2 \rightarrow 6\ CO_2 + 6\ H_2O$). This has been shown by Petsch et al. (2000) who studied black shales chemical weathering. Numerous authors (Ross; Duchauffour; Guillet; Tissot and Pelet) have shown that the organic matter is reactive, subject to oxidising alteration generally mediated by biological activity. It is thus generally admitted that about 99% of the matter produced by the current biomass is effectively mineralised (Tissot and Welte, 1984). However, even the alteration of this rather fragile material in soils or rivers usually leaves a refractory organic residue (Balesdent and Lin). Effectively, biopolymers such as proteins and polysaccharides are known to be easily metabolised by living organisms (Tissot; Ramanampisoa and Disnar), whereas others such as lignin, sporopollenin, cutan and algaenan are intrinsically resistant to biodegradation (Tegelaar et al., 1989). In the case of the bedrock organic yield, it must be considered that the fossil organic matter has usually undergone extensive alteration in the course of burial diagenesis (defunctionalisation, carbonisation) (Tissot and Welte, 1984). As a consequence of this evolution, it has acquired a refractory character, especially against biological attacks (Pelet; Caratini; Armentrout; Tissot; Botz and Tyson). Except for the presence of free hydrocarbons, this organic material mainly occurs under the particulate form and is usually referred to as kerogen (Durand and Tissot). Only a very small proportion of this material can be assimilated to humic substances and can evenly been solubilised in aqueous media (Huc and Durand, 1977). As a logical consequence of the intrinsic physico-chemical and biological resistance of the organic matter from bedrock formations, we suggest that it could contribute in a significant way to the organic stock of soils and rivers. This possibility is fully supported by the frequent observation of recycled organic matter in ancient sedimentary rocks, by organic petrographers and palynologists.

The extent of alteration that the recycled organic matter can suffer in the supergene environment cannot be simply ruled out. It is effectively well known that the organic matter contained in ancient rocks suffers alteration during oxidative weathering (Cowie and Hoefs). For example, Capus et al. (1979) and Bach (1980), who studied outcropping Permian shales in the Aumance basin (France), observed a decrease of their carbon organic content from 5% to 0.4% as a result of their supergene alteration. This loss is accompanied by the transformation of the organic matter or most likely of a part of it into aromatic humic acids. A variable part of this organic matter might also be mineralised and might thus disappear without further contributing in a significant way to the organic stock of soils and watersheds.

All these studies suggest different fates for the organic matter released from ancient rocks. Accordingly, it must be admitted that the effective contribution of the considered process to the global carbon cycle remains unknown.

However, at least in a first approach, we would consider three main contrasted hypotheses depending of the possible fate of the recycled OM. In a first case, we would consider the consequences of a complete mineralisation of the organic carbon released from weathered bedrock formation. In the second and third cases, we would suggest that this organic carbon is not mineralised at all and supplies either soils or rivers.

4.3. Hypothesis one: the inherited organic yield is completely mineralised

The hypothesis is purely theoretical since there is ample evidence that a non-negligible part of the organic matter released from bedrock formations is effectively recycled, i.e. resists to destruction during transport and (re-)sedimentation. The global organic carbon cycle understanding needs the knowledge of carbon fluxes between atmosphere, lithosphere, ocean and soils. Some fluxes are, up to now, well described, but others are still unknown (missing carbon: Amiotte-Suchet, 1995). Berner et al. (1983), Meybeck (1987) and Probst (1992) calculated the mineral fluxes in rivers due to rock weathering. These authors consider that the rock chemical weathering can be compared to a carbon sink because it needs atmospheric CO_2 to produce bicarbonates. Amiotte-Suchet (1995) estimated that 0.3 Gt of carbon/year are lost by the atmosphere during rock chemical weathering. However, if we admit that the 0.1 Gt/y of organic carbon assumed to be released from weathered carbonates and shales are totally mineralised, this necessarily entails an equal supply of carbon to the atmosphere. Consequently, the carbon sink due to the chemical weathering of the considered ancient formations would not be as an efficient sink as it is supposed up to now.

4.4. Hypothesis two: the inherited organic yield is not mineralised and supplies soils

The amount of global soil organic carbon evaluated is another one of the key components of understanding the global organic carbon cycle (Arthur, 1982). It is based on several measurements of the organic stock in soils under various vegetal covers and under different climates. The extrapolation at a global scale is allowed, for one part by the relationships deduced from these measurements between vegetation, climate and organic matter and for the other part, through climate, vegetation (Adams and Faure, 1996) or soil maps (Batjes, 1996). The evaluation of the past global soil organic amounts quite naturally lies on palaeovegetation maps (Adams et al., 1990). The possibility that a significant inherited organic yield related to carbonate rocks dissolution is supported by the conclusions of Lichtfouse et al. (1997) and Di; Di and Di and suggests that the soil organic matter is not only issued from the local vegetal production. This assumption implies that the simple account of the climatic and vegetation data is not sufficient to describe and evaluate the soil organic stock. It appears necessary to define precisely the bedrock composition and the fate of its organic matter content during weathering.

4.5. Hypothesis three: the inherited organic yield is not mineralised and supplies rivers

There exists many kinds of evaluation of the total amounts of organic matter occurring in rivers. As an example, Aitkenhead and Mc Dowell (2000) recently estimated dissolved organic carbon fluxes at local and global scales using soils carbon–nitrogen ratio (C/N). For their part, Ludwig et al. (1996) propose global dissolved and particulate organic fluxes calculations using global runoff maps (such as those produced by Korzoum et al., 1977) and the average organic carbon content of soils as this has been already defined. In making these estimates, Ludwig et al. (1996) assume that the organic matter of soils and watersheds only derive from the surrounding vegetation. The present hypothesis suggests the contrary and bring support to previous works that give evidence for a significant contribution of inherited organic matter in rivers (Gadel; Dow; Di; Disnar; Di; Di; Buillit and Noel). It also joins the conclusion of Meybeck (1993) who considers that about 45% of the particulate organic matter occurring in the world's present rivers originate from rocks. The present hypothesis in fact implies a re-evaluation of the total amount of the organic matter occurring in rivers, taking into account the contribution of the fossil organic matter from weathered sedimentary rocks.

5. Conclusion

This study proposes an initial estimation of the annual organic yield produced by the dissolution of carbonate rocks and shales. The calculated value amounts to 0.1 Gt/year. Despite large uncertainty arising from the global scale evaluation, we suggest that the annual inherited organic yield might be a non-negligible element of the carbon cycle. This yield resulting from rock chemical weathering varies depending on the initial organic content of the altered rock and on local climatic parameters. However, such yield does not necessarily constitute a direct supply to soils and the rivers because a part of the produced organic matter can be mineralised, thus escaping recycling. Depending on the real fate of the organic carbon released from weathered ancient formations, i.e. mineralisation or recycling, this process might affect the efficiency of chemical weathering as a carbon sink, the global soil organic carbon amount estimation, or the evaluation of the total amount of the organic matter occurring in rivers.

Whatever the hypothesis considered, this study suggests that the inherited organic yield is a key component of the global organic carbon cycle understanding that has been omitted up to now.

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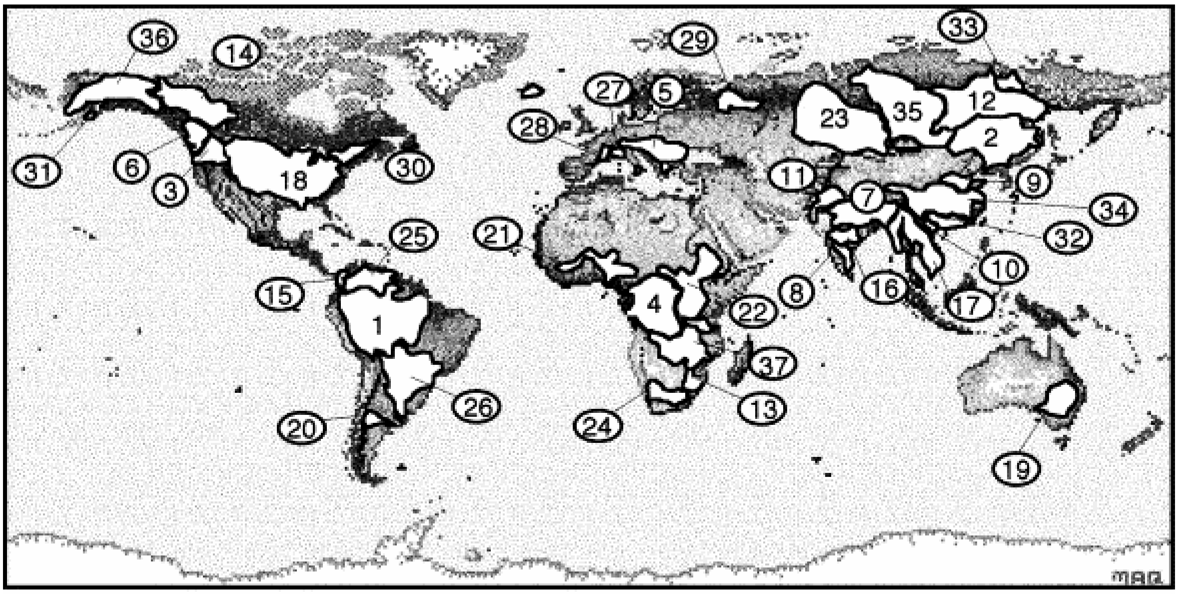
Figures



1 - Amazon
2 - Amour
3 - Columbia
4 - Congo
5 - Danube
6 - Fraser
7 - Ganges/Brahmapoutre
8 - Godavari
9 - Huange
10 - Hungo
11 - Indus
12 - Lena
13 - Limpopo
14 - Mackensie
15 - Magdalena
16 - Mehandi
17 - Mekong
18 - Mississippi
19 - Murray
20 - Negro
21 - Niger
22 - Nil
23 - Ob
24 - Orange
25 - Orenoque
26 - Parana
27 - Pô
28 - Rhône
29 - Severnaia
30 - Saint Laurent
31 - Susitna
32 - Xi Jiang
33 - Yana
34 - Yangtse
35 - Yenisei
36 - Yukon
37 - Zambeze

Fig. 1. Location of the studied major world watersheds.

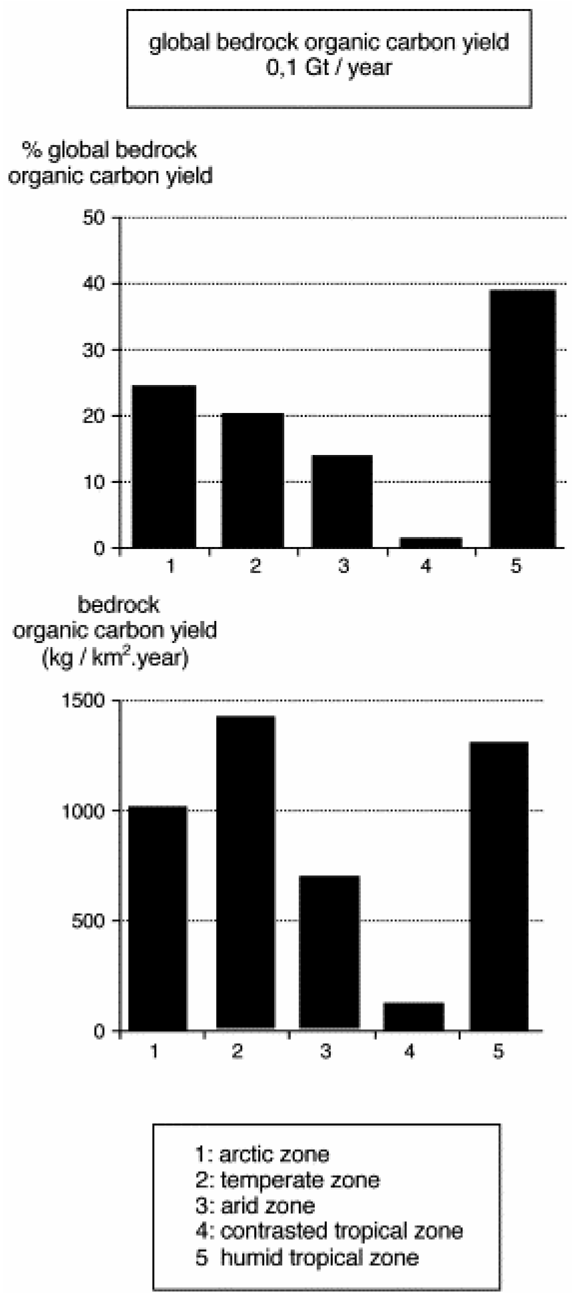


Fig. 2. Bedrock organic yield in the climatic zones.

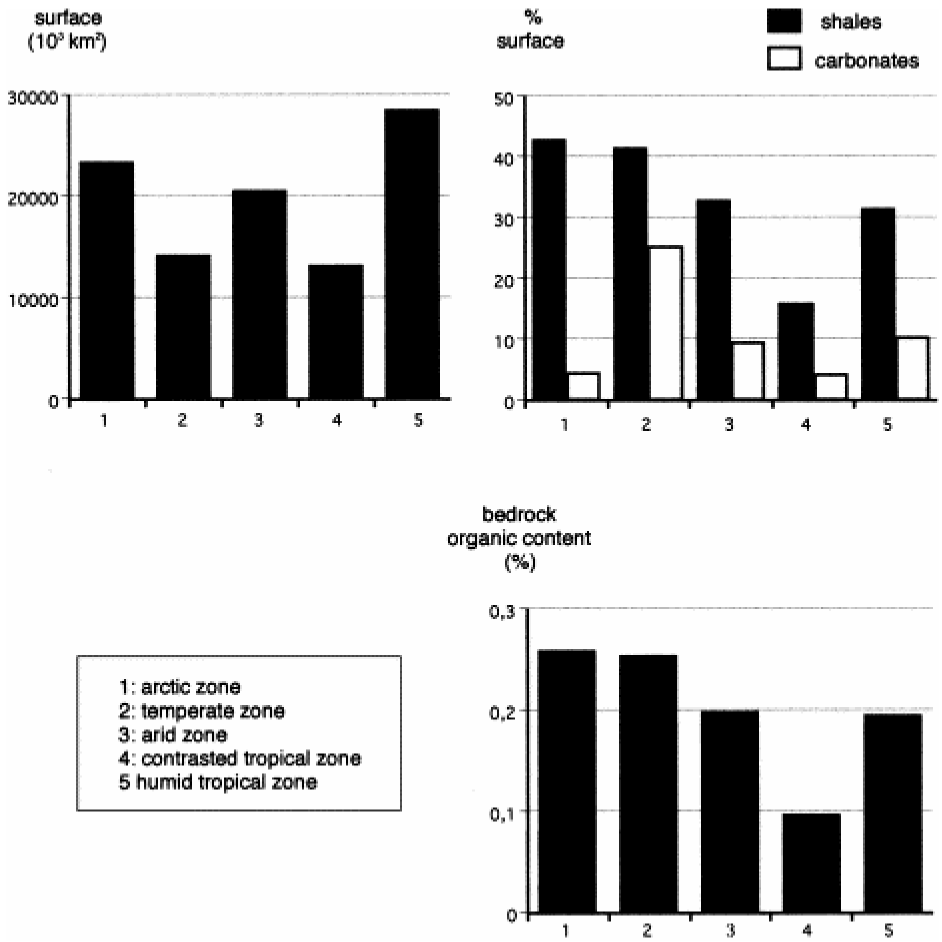


Fig. 3. Climatic zones characterization: surface*, bedrock organic content and proportions of shales and carbonates

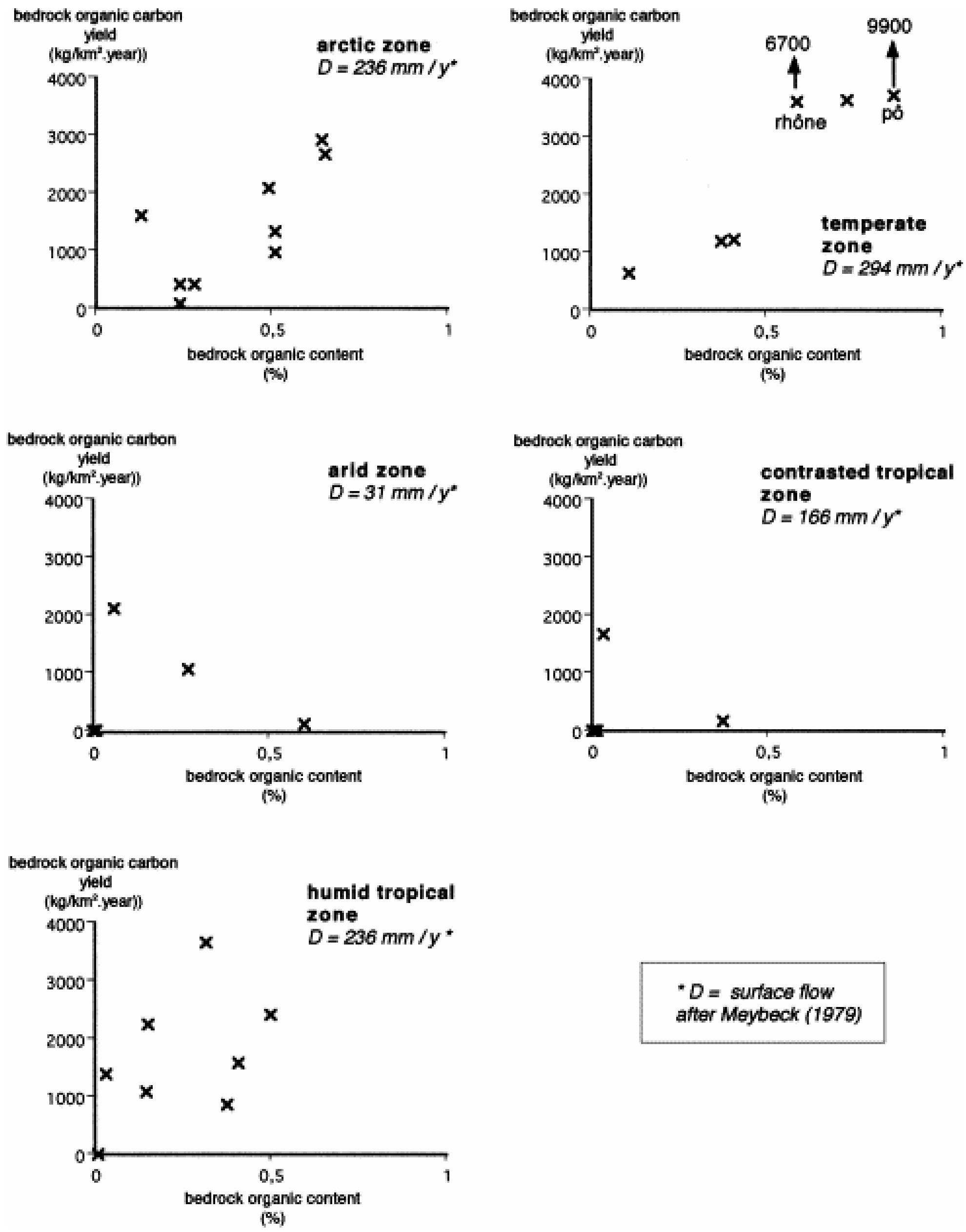


Fig. 4. Relationships between the bedrock organic yield and the bedrock organic content for each climatic zone.

Tables

Table 1. Average value of the bedrock organic carbon yield in the major world watersheds

	Surface[a] (1000 km^2)	Length[a] (km)	F_{CaCo_3}[b] (1000 moles/ km^2/year)	F_{CaCo_3}[c] (t/km^2 year)	F_{CaCo_3}[c] (t/year)	Surface shales[d] (km^2)	Surface carbonates[d] (km^2)	Bedrock organic carbon yield[e] (t/year)	Bedrock organic carbon yield[e] (kg/km^2 year)
Amazon	5908	6299	129	12.9	76,213,200	2,986,494	232,184.4	9,433,077	1597
Amour	1923	4352	7	0.7	1,346,100	582,284.4	0	179,480	93
Columbia	670	1850	159	15.9	10,653,000	49,379	0	1,420,400	2120
Congo	3698	4370	19	1.9	7,026,200	0	495,162.2	5562	2
Danube	778	2859	147	14.7	11,436,600	381,297.8	238,846	941,065	12,101
Fraser	247	1375	156	15.6	3,853,200	150,274.8	0	513,760	2080
Ganges–Brahma	1669	5401	371	37.1	61,919,900	642,898.8	223,312.2	6,140,200	3679
Godavari	322	1448	125	12.5	4,025,000	13,620.6	0	536,667	1667
Huange	814	4668	62	6.2	5,046,800	0	138,217.2	3995	5
Hungo	165	1200	353	35.3	5,824,500	23,875.5	82,005	178,690	1083
Indus	916	2896	147	14.7	13,465,200	291,196.4	245,304.8	979,340	1069
Lena	2438	4269	38	3.8	9,264,400	847,448.8	167,003	1,033,101	424
Limpopo	342	1770	0	0	0	0	76,744.8	0	0
Mackensie	1616	4240	123	12.3	19,876,800	1,016,948.8	225,108.8	2,172,766	1345
Magdalena	276	1537	294	29.4	8,114,400	49,928.4	37,812	618,431	2241
Mehandi	195	1295	105	10.5	2,047,500	7,410	0	273,000	1400
Mekong	849	4023	235	23.5	19,951,500	520,012.5	158,678.1	2,041,937	2405
Mississippi	3265	3778	127	12.7	41,465,500	1,449,007	588,026.5	3,942,239	1207

Murray	1140	2589	9	0.9	1,026,000	850,326	10,260	135,179	119
Negro	178	729	0	0	0	0	0	0	0
Niger	1550	4183	19	1.9	2,945,000	0	49,600	2331	2
Nil	1905	6689	22	2.2	4,191,000	0	89,535	3317	2
Ob	2249	3680	79	7.9	17,767,100	1,420,693.3	101,429.9	2,212,024	984
Orange	726	2092	1	0.1	72,600	0	87,265.2	57	>0
Orenoque	1020	2061	65	6.5	6,630,000	480,318	0	884,000	867
Parana	2868	4499	13	1.3	3,728,400	1,322,434.8	34,416	484,586	169
Pô	70	652	746	74.6	5,222,000	70,000	0	696,267	9947
Rhone	99	813	725	72.5	7,177,500	69,092.1	29,907.9	669,606	6764
Severnaia	262	740	295	29.5	7,729,000	239,022.6	18,523.4	956,855	3652
St. Laurent	1099	3057	276	27.6	30,332,400	105,504	529,718	691,743	629
Susitna	51	600	219	21.9	1,116,900	40,631.7	0	148,920	2920
Xi Jiang	464	1957	686	68.6	31,830,400	0	0	25,196	54
Yana	240	1368	31	3.1	744,000	70,848	0	99,200	413
Yangtse	1827	5525	356	35.6	65,041,200	114,918.3	1,104,786.9	863,707	473
Yenisei	2553	4129	133	13.3	33,954,900	401,076.3	42,890.4	4,092,545	1603
Yukon	833	3701	199	19.9	16,576,700	678,478.5	0	2,210,227	2653
Zambeze	1420	2735	29	2.9	4,118,000	0	99,542	3260	2

[a] From Pinet and Souriau (1988).
[b] From Amiotte-Suchet (1995).
[c] This work.
[d] Calculated from Pinet and Souriau (1988) and Amiotte-Suchet (1995).

Table 2. Average value of the bedrock organic carbon yield for the different climatic zones

	Surface[a] (1000 km^2)	Bedrock organic carbon content (%)	Organic carbon yield, OY (t/year)	Organic carbon yield, OY (kg/km^2 year)	Surface shales (km^2)	Surface carbonates (km^2)
Arctic zone						
Amour	1923	0.24	179,480	93	582,284.4	0
Fraser	247	0.49	513,760	2080	150,274.8	0
Lena	2438	0.28	1,033,108	424	847,448.8	167,003
Mackensie	1616	0.51	2,172,766	1345	1,016,948.8	225,108.8
Ob	2249	0.51	2,212,024	984	1,420,693.3	101,429.9
Susitna	51	0.64	148,920	2920	40,631.7	0
Yana	240	0.24	99,200	413	70,848	0
Yenisei	2553	0.13	4,092,545	1603	401,076.3	42,890.4
Yukon	833	0.65	2,210,227	2653	678,478.5	0
Total watersheds surface: 12,150		total OY (watersheds): 12,662,029 t/year				
Total zone surface: 23,300		total OY (zone): 24,281,916 t/year				
		mean OY (zone): 1042 kg/km^2 year				
Temperate zone						
Danube	778	0.41	941,065	1210	381,297.8	238,846
Mississippi	3265	0.37	3,942,239	1207	1,449,007	588,026.5
Pô	70	0.8	696,267	9947	70,000	0
Rhone	99	0.58	669,607	6764	69,092.1	29,907.9
St. Laurent	1099	0.11	691,743	629	105,504	529,718
Severnaia	262	0.73	956,855	3652	239,022.6	18,523.4
Total watersheds surface: 5573		total OY (watersheds): 7,897,775 t/year				
Total zone surface: 14,100		total OY (zone): 19,981,811 t/year				
		mean OY (zone): 1417 kg/km^2 year				
Arid zone						
Columbia	670	0.06	1,420,400	2120	49,379	0
Indus	916	0.27	979,340	1069	291,196.4	245,304.8
Murrey	1140	0.6	135,179	119	850,326	10,260
Negro	178	0	0	0	0	0
Orange	726	0.01	57	>0	0	87,265.2
Total watersheds surface: 3630		total OY (watersheds): 2,534,976 t/year				
Total zone surface: 20,500		total OY (zone): 14,322,614 t/year				
		mean OY (zone): 698 kg/km^2 year				

Contrasted tropical zone						
Godavari	322	0.03384	536,667	1667	13,620.6	0
Limpopo	342	0.013464	0	0	0	76,744.8
Niger	1550	0.00192	2332	2	0	49,600
Nil	1905	0.00282	3317	2	0	89,535
Parana	2868	0.3696	484,586	169	1,322,434.8	34,416
Zambeze	1420	0.004206	3260	2	0	99,542
Total watersheds surface: 8407		total OY (watersheds): 1,030,160 t/year				
Total zone surface: 13,200		total OY (zone): 1,617,476 t/year				
		mean OY (zone): 123 kg/km^2 year				
Humid tropical zone						
Amazon	5908	0.406758	9,433,077	1597	2,986,494	232,184.4
Congo	3698	0.008034	5562	2	0	495,162.2
Huange	814	0.010188	3995	5	0	138,217.2
Hungo	165	0.14558	178,690	1083	23,875.5	82,005
Magdalena	276	0.15294	618,431	2241	49,928.4	37,812
Mehandi	195	0.03	273,000	1400	7410	0
Mekong	849	0.501214	2,041,937	2405	520,012.5	158,678.1
Orenoque	1020	0.37672	884,000	867	480,318	0
Ganges–Brahma	1669	0.316188	6,140,200	3679	642,898.8	223,312.2
Total watersheds surface: 15,058		total OY (watersheds): 19,604,088 t/year				
Total zone surface: 28,500		total OY (zone): 37,104,298 t/year				
		mean OY (zone): 1302 kg/km^2 year				

	Organic carbon yield, OY (t/year)	Organic carbon yield, OY (%)	Organic carbon yield, OY (kg/km^2 year)	Surface shales (%)	Surface carbonates (%)	Bedrock organic carbon content (%)
Arctic zone	24,281,916	25	1042	42.87	4.42	0.26
Temperate zone	19,981,811	21	1417	41.52	25.21	0.25
Arid zone	14,322,614	15	698	32.81	9.44	0.2
Contrasted tropical zone	1,617,476	2	123	15.89	4.16	0.1
Humid tropical zone	37,104,297	38	1302	31.28	10.68	0.2
Total	97,308,114	100	977			

[a] From Pinet and Souriau (1988).